Supersoft Sources and Quasisoft Sources: Are Galaxies Teeming with Intermediate Mass Black Holes?

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What does an accreting intermediate mass black hole look like?

Luminosity

- It could be bright
- $L_{Edd} = 4\pi G M m_p c/\sigma_T = 1.26 \times 10^{38} (M/M_{Sun})$ erg/s
- For a 100-1000 M_{Sun} accreting BH, L can be as high as 10^{40}-10^{41} erg/s
- Finding a source so bright that it is super-Eddington for a stellar-mass BH may be a clue that the source is an intermediate-mass BH.
- ULXs are thought to be IMBH candidates.

But it need not be bright

- The actual value of L depends on m_{dot}
- $L=(\xi/0.1)(0.1m_{dot}\, c^2\,)$
  $= (\xi/0.1)(m_{dot} / 10^{-8}\, M_{Sun}\, yr^{-1})\ 5.7 \times 10^{37}$ erg/s
- The value of m_{dot} depends largely on the state of the donor and on the mechanism that fuels mass transfer. (e.g., gravitational radiation, nuclear evolution of the donor, irradiation of the donor)

Spectra

- If the accretion is mediated by a disk which is geometrically thin, but optically thick, the spectrum must be soft.
- kT_{Iso}=42eV ((ξ/0.1) L_{obs}/3x10^{37}erg/s$)^{1/4}$
  ($10^3 M_{Sun}$/M$)^{1/2}$ g
- ($M/10^3 M_{Sun}$)=(42eV/$kT_{Iso})^2$ ((ξ/0.1) L_{obs}/3x10^{37} erg/s$)^{1/2}$ g^2
  g is a factor of order unity.
- The above is a lower limit on M; spectral hardening, BH spin, and orientation effects, will increase the estimate for a given set of values for L and T.

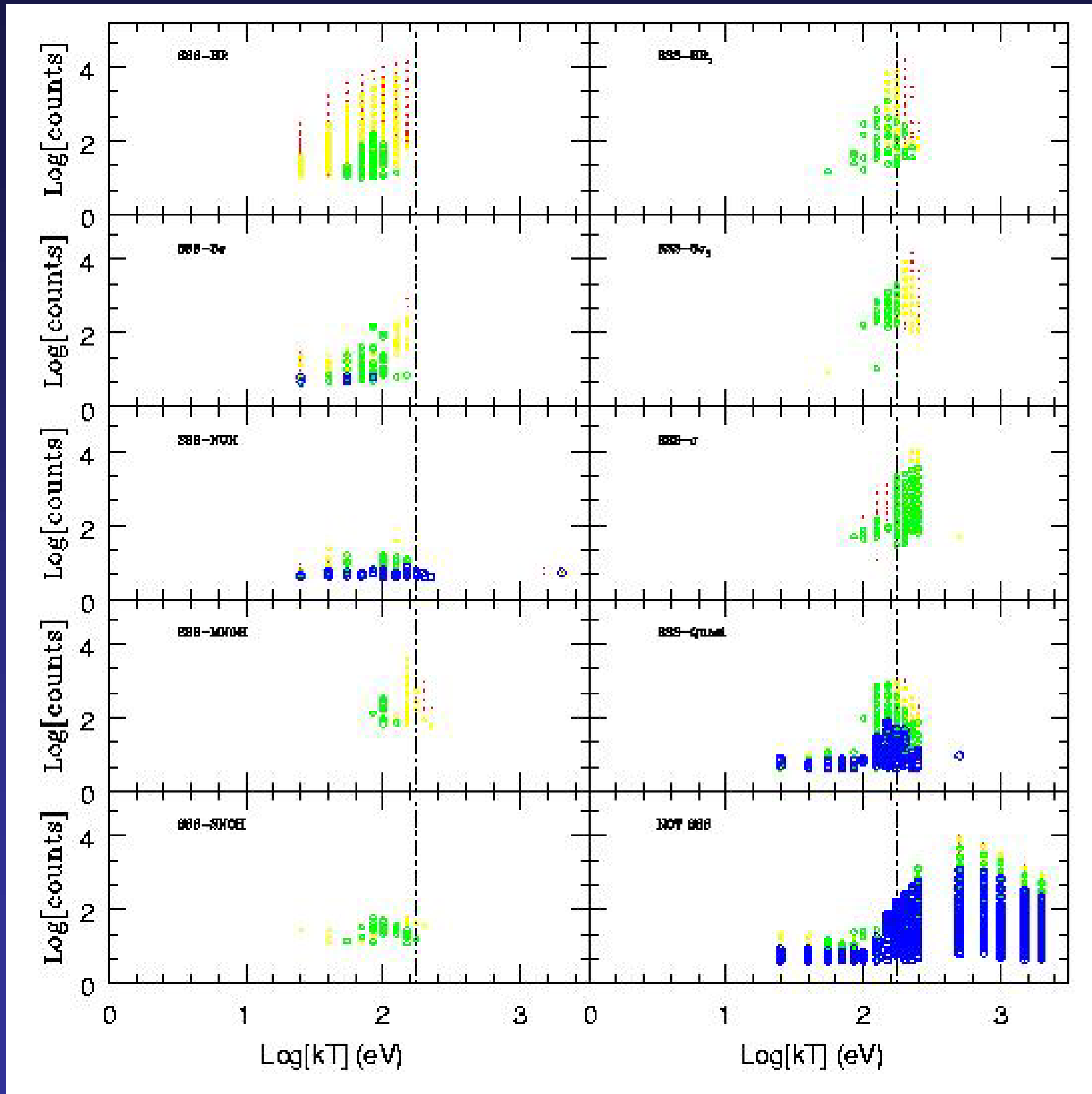
- Note that the model may break down for $L << L_{Edd}$.
- One puzzle is: Why are ULXs not generally soft?
- It has been suggested that the high computed luminosities of some of these sources is due to beaming, not to a high-mass accretor (e.g., King et al. 2001).
- Some ULXs *are* soft (e.g., Mukai et al. 2003; Miller et al. 2003; Kong & Di Stefano 2003; Fabbiano et al. 2003).

Are There Soft X-Ray Sources in Galaxies?

- The answer is “yes”: there are many.
- Some may be accreting WDs, some may be SNRs, etc.
- But a natural model for some is that they are accreting IMBHs.

Supersoft Sources and Quasisoft Sources

- SSSs are sources with kT ~ tens of eV, and with L typically between 10^{36}-10^{38} erg/s.
- Some may be nuclear-burning WDs; some of these may be progenitors of Type Ia supernovae.
- We have developed a method to search for SSSs in external galaxies. (Di Stefano & Kong 2003 a,b,c)
- Each spiral galaxy is likely to contain over 1000 SSSs
- We have tested our algorithm on simulated data.


Log[counts]
Log[kT] (eV)

- All sources picked up in any but the first 2 steps are referred to as candidate ***Quasisoft Sources (QSSs)***.
- QSSs typically have 100eV < kT < 250 eV.
- Or else they have a softer dominant spectrum, but may include a small hard component.
- Are QSSs just an intriguing possibility?

- We have tested our algorithm on real data *Chandra* and some *XMM-Newton* from ~20 galaxies.
- We find SSSs *and* QSSs.

GALAXY PROPERTIES AND SSSs

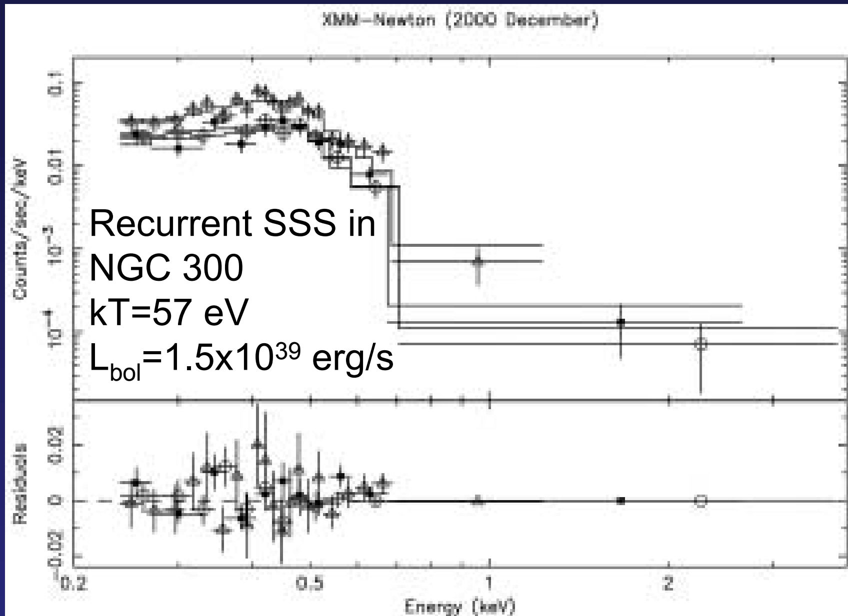
Galaxy	Type	N_H ($\times 10^{20}$ cm^{-2})	Mass ($10^9 M_\odot$)	Size (arcmin)	M_{BH} ($10^6 M_\odot$)	D (Mpc)	Exp (ks)	Date
M 31	Sb	6.7	300	190'/60'	70	0.76	38.15	10/05/01
M 32	E2	6.3	3	8.7'/6.5'	2.9	0.81	46.46	7/24/01
M 33	Sc	5.6	390	70.8'/41.7'	0	0.94	46.85	8/30/00
NGC 3115	S0	4.3		7.3'/2.5'	1000*	9.7	37.45	6/14/01
NGC 5845	E	4.3		0.8'/0.5'	240	25.9	30.25	5/24/00
NGC 1313	Sb	3.9		9.1'/6.9'			20.16	10/13/02
M 104	Sa	3.8	590	23.0'/6.0'	1100*	9.8	18.75	5/31/01
M 83	Sab	3.8	83	11.0'/10.0'		4.6	51.64	4/29/00
NGC 3379	E1	2.8		4.5'/4.5'	100*	10.6	31.92	2/13/01
M 84	E1	2.6		6.5'/5.6'	1600	18.4	28.55	5/19/00
NGC 4552	E	2.6		5.1'/4.7'	470	18.4	55.14	4/22/01
NGC 4649	E2	2.2		7.4'/6.0'	2000	16.8	37.35	4/20/00
NGC 4697	E4/E6	2.1		7.2'/4.6'	170	11.7	39.76	1/15/00
NGC 4151	Sab	2.0	95	6.2'/3.9'	1×10^{5} *	20.3	27.95	3/7/00
NGC 4472	E2	1.7		10.2'/8.3'			40.1	7/18/01
M 51	Sc	1.6	220	5.8'/4.6'	40	8.4	15.06	6/20/00
NGC 1399	E1	1.3		6.9'/6.5'			56.66	1/18/00
NGC 4258	Sbc	1.2	180	22.0'/9.0'	39	7.2	21.30	5/28/01
M 101	Sc	1.2	280	29.0'/27.0'		7.5	98.65	3/26/00

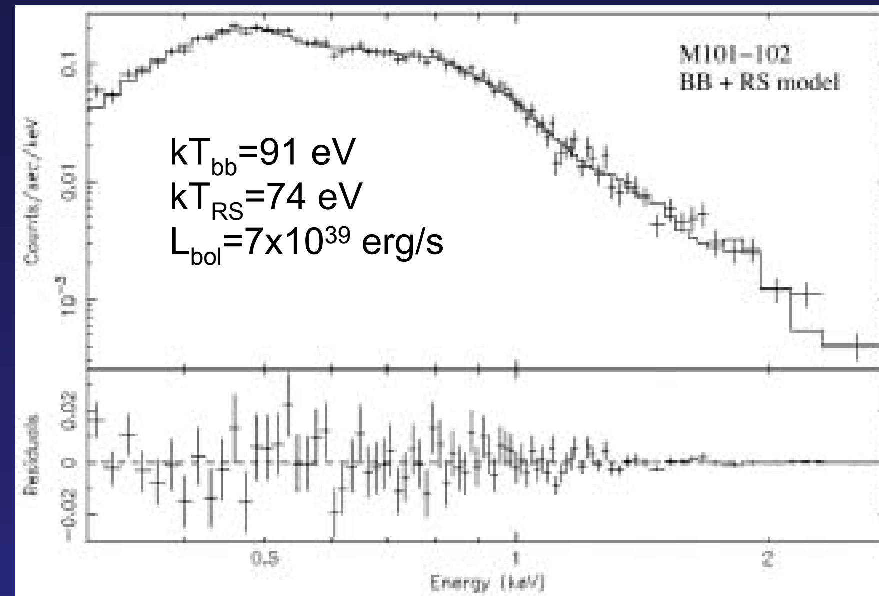
* Values from Kormendy 2000

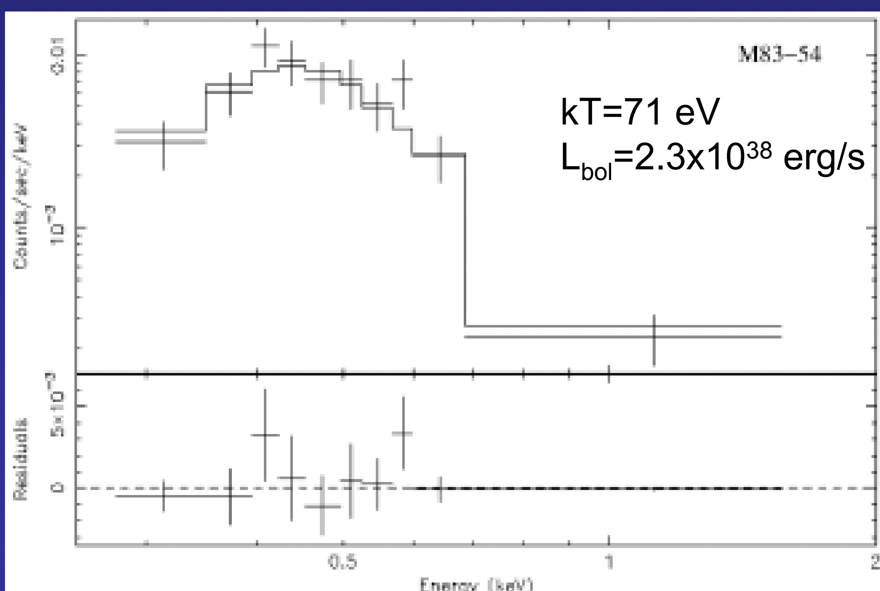
GALAXY PROPERTIES AND SSSs

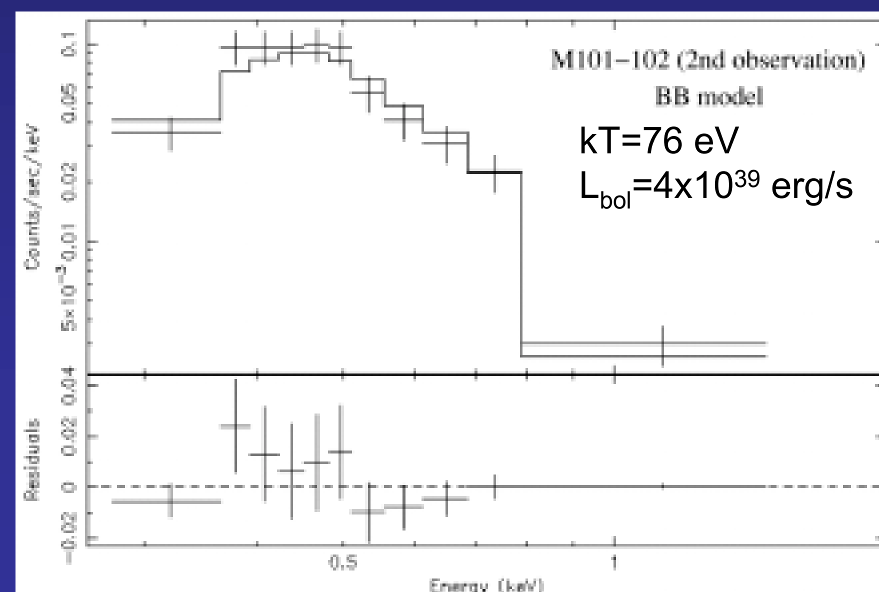
Galaxy	N_X	N_{VSS}	N_{SSS}	N_{QSS}	$\frac{N_{VSS}}{N_X}$	$\frac{N_{SSS}}{N_{VSS}}$	$\frac{N_{QSS}}{N_{VSS}}$
M 32	18	2	2	0	0.11	1.0	0.0
M 31	93	16	11	5	0.17	0.69	0.31
M 33	34	6	3	3	0.18	0.50	0.50
M 101	113	43	32	11	0.38	0.74	0.26
M 83	119	52	19	33	0.44	0.37	0.63
NGC 4258	38	9	3	6	0.24	0.33	0.67
NGC 3115	52	3	0	3	0.06	0.0	1.0
NGC 4697	72	16	3	13	0.22	0.19	0.81
NGC 3379	42	6	0	6	0.14	0.0	1.0
NGC 1399	233	75	4	71	0.32	0.05	0.95
M 51	54	13	3	10	0.24	0.23	0.77
NGC 4472	134	30	5	25	0.22	0.17	0.83
M 104	87	10	4	6	0.11	0.40	0.60
NGC 4552	103	11	3	8	0.11	0.27	0.73
NGC 4649	163	33	5	28	0.20	0.15	0.85
M 84	54	14	6	8	0.26	0.43	0.57
NGC 4151	27	4	3	1	0.15	0.75	0.25
NGC 5845	44	19	6	13	0.43	0.32	0.68
NGC 1313	17	2	1	1	0.12	0.50	0.50

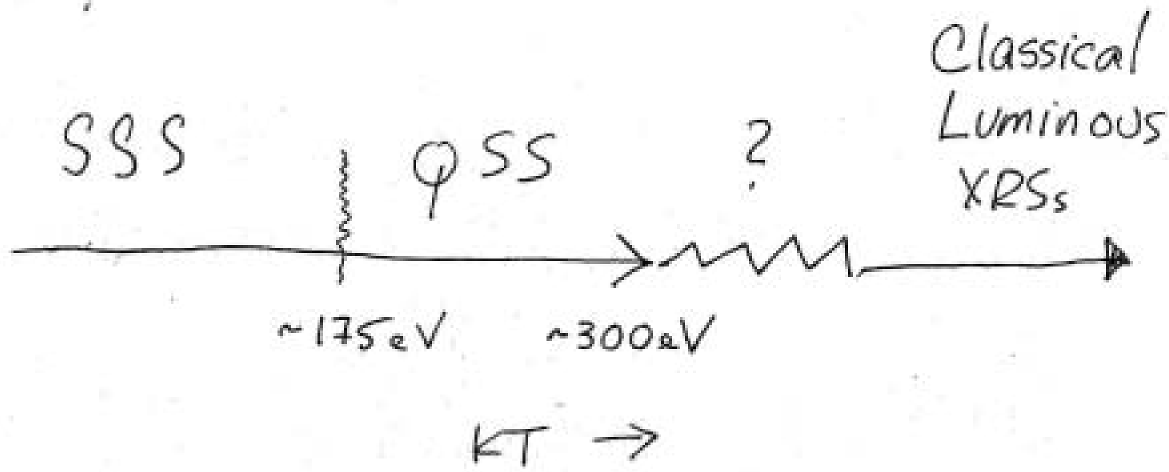
SSSs

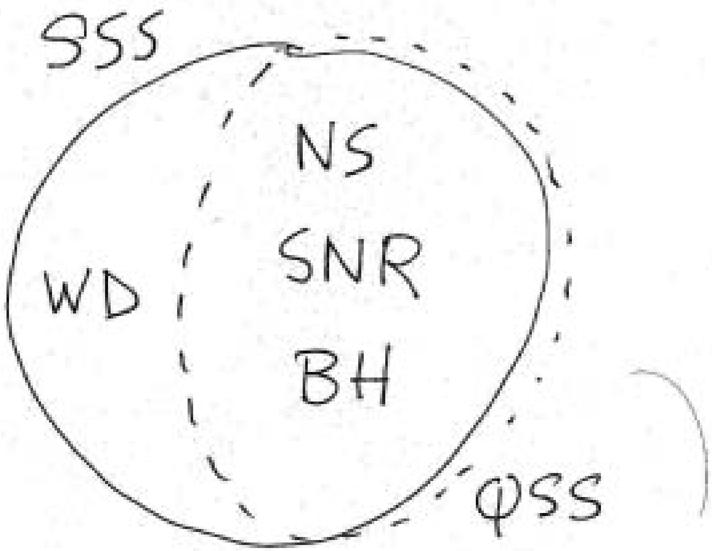

XMM-Newton (2000 December)
Recurrent SSS in NGC 300
kT=57 eV
L_{bol}=1.5x10^{39} erg/s
Counts/sec/keV
Residuals
Energy (keV)

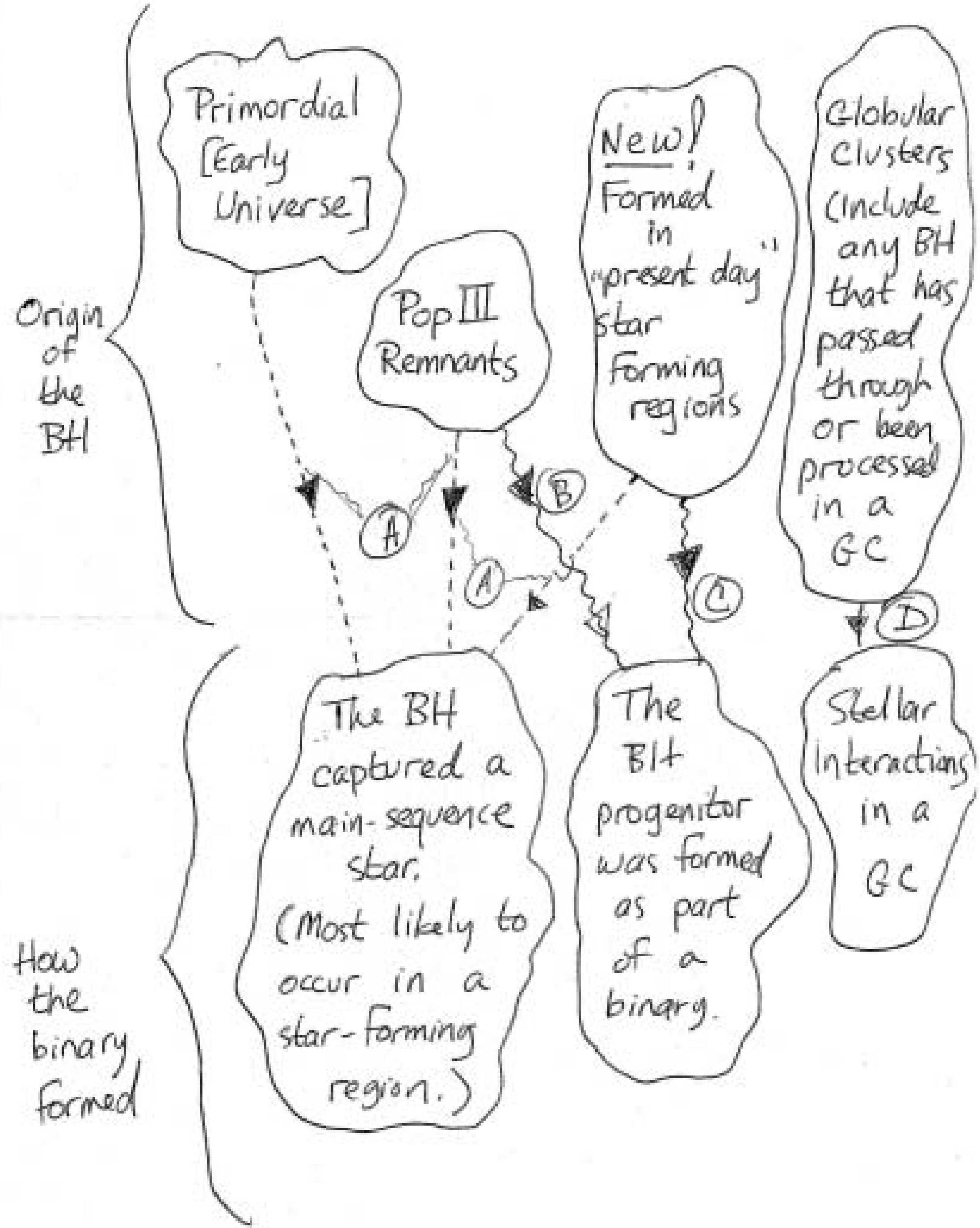

M101-102
BB + RS model
kT_{bb}=91 eV
kT_{RS}=74 eV
L_{bol}=7x10^{39} erg/s
Counts/sec/keV
Residuals
Energy (keV)


M83-54
kT=71 eV
L_{bol}=2.3x10^{38} erg/s
Counts/sec/keV
Residuals
Energy (keV)

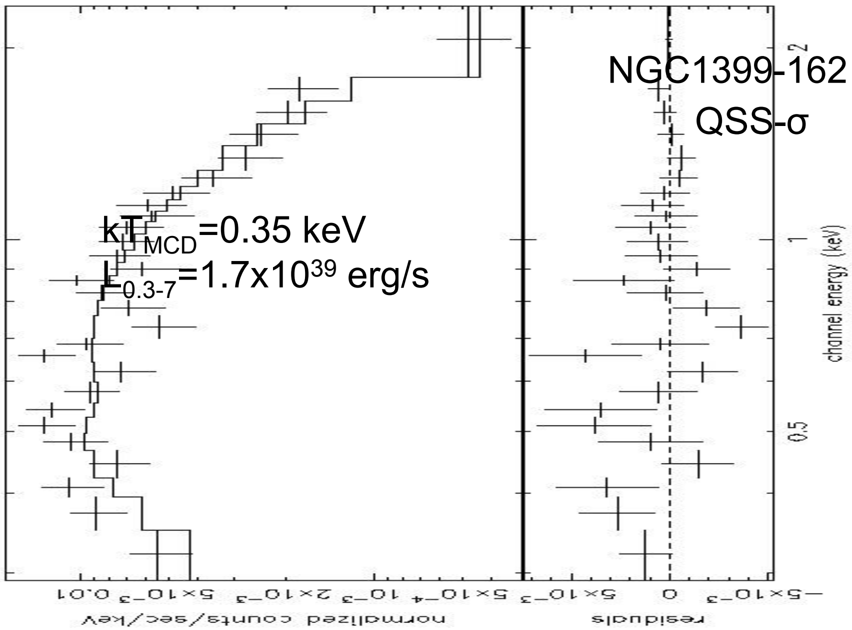

M101-102 (2nd observation)
BB model
kT=76 eV
L_{bol}=4x10^{39} erg/s
Counts/sec/keV
Residuals
Energy (keV)


SSS
QSS
?
Classical Luminous XRSs
~175eV
~300eV
KT →

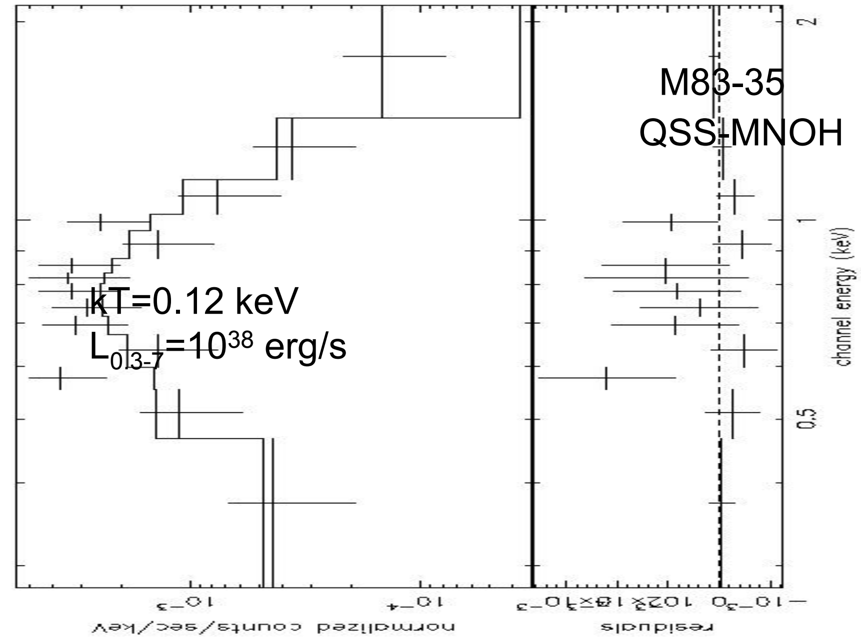

SSS
WD
NS
SNR
BH
QSS


Origin of the BH
Primordial [Early Universe]
Pop III Remnants
New! Formed in "present day" star forming regions
Globular Clusters (include any BH that has passed through or been processed in a GC
A
A
B
C
D
How the binary formed
The BH captured a main-sequence star. (Most likely to occur in a star-forming region.)
The BH progenitor was formed as part of a binary.
Stellar Interactions in a GC

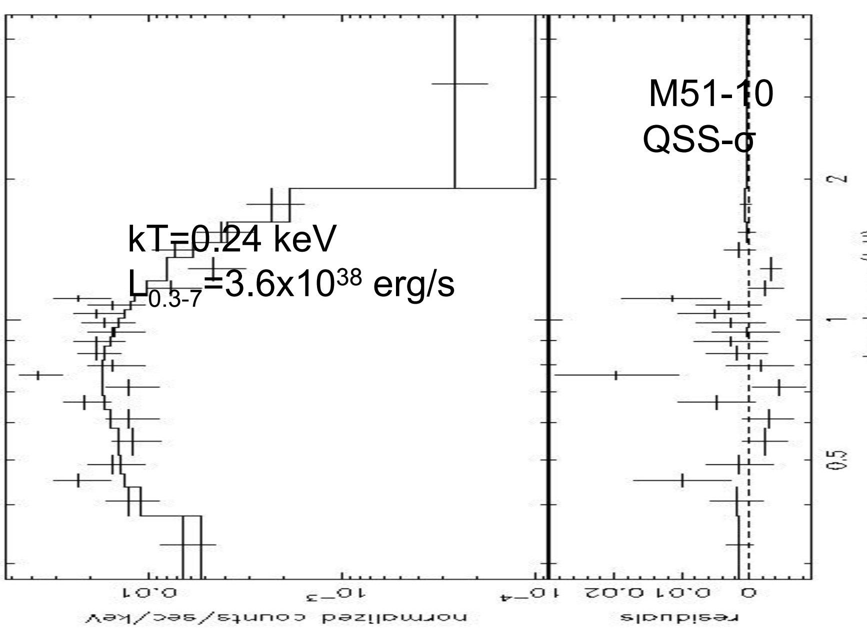
QSSs



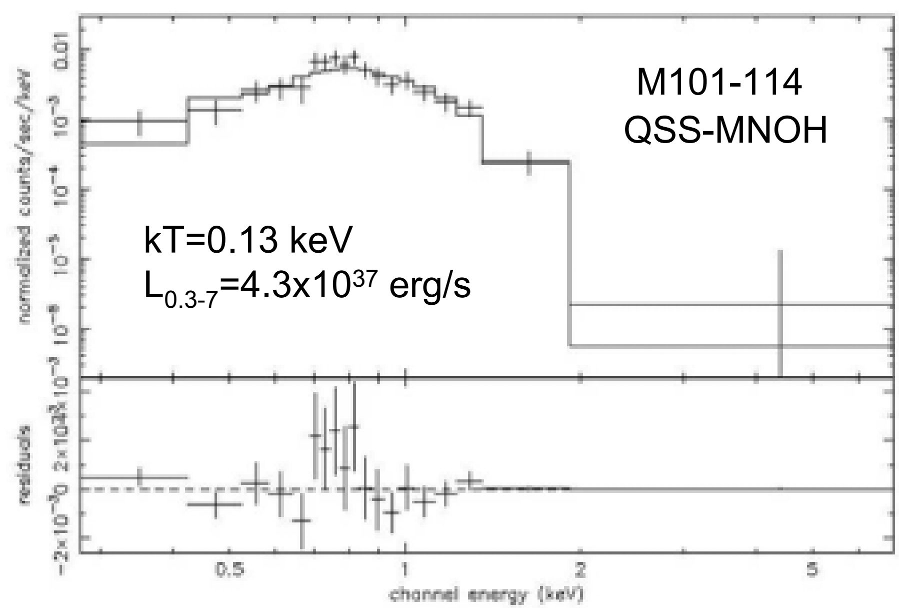
NGC1399-162
QSS-σ
kT_MCD=0.35 keV
L_0.3-7=1.7x10^39 erg/s



M83-35
QSS-MNOH
kT=0.12 keV
L_0.3-7=10^38 erg/s

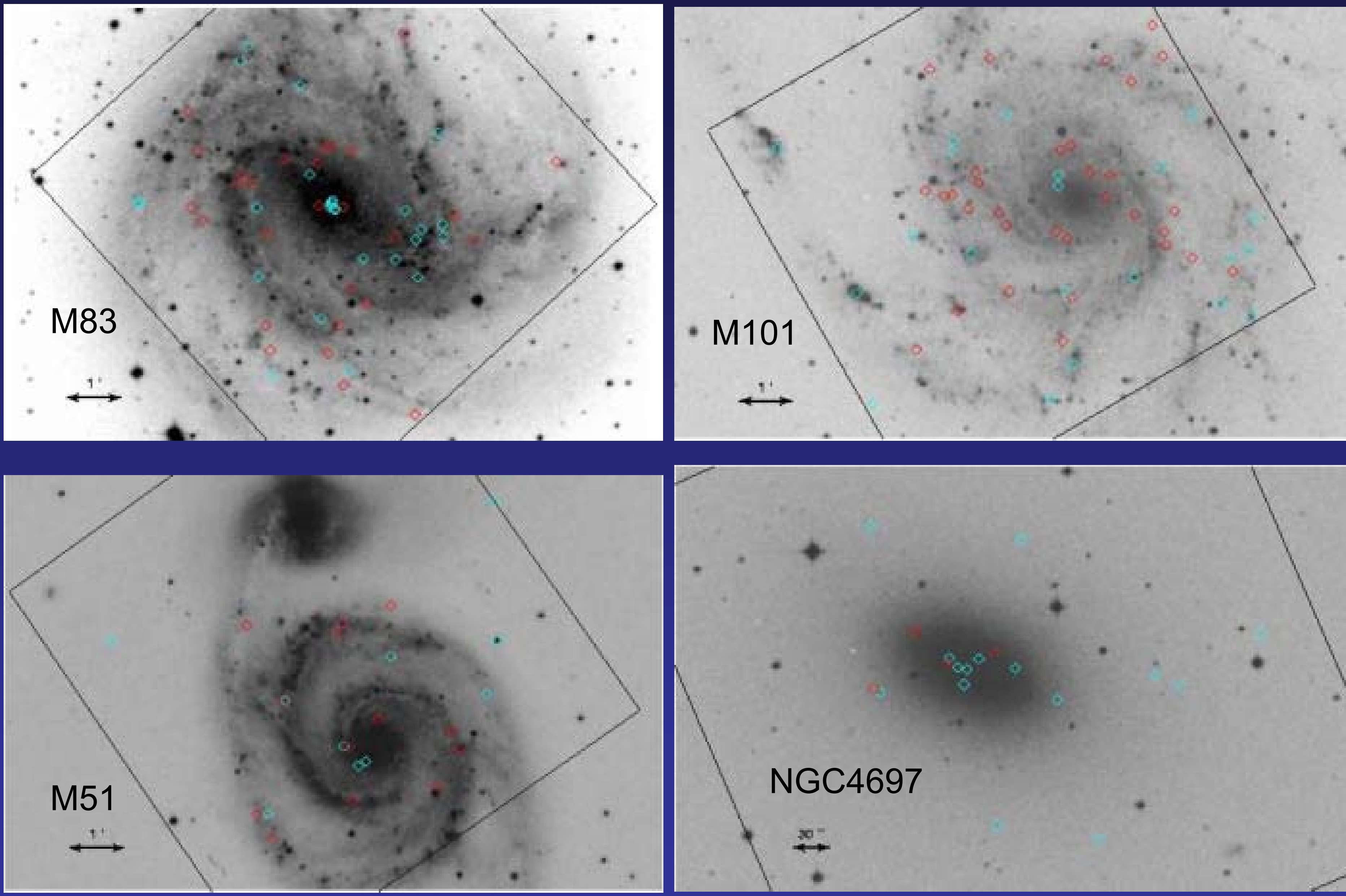


M51-10
QSS-σ
kT=0.24 keV
L_0.3-7=3.6x10^38 erg/s



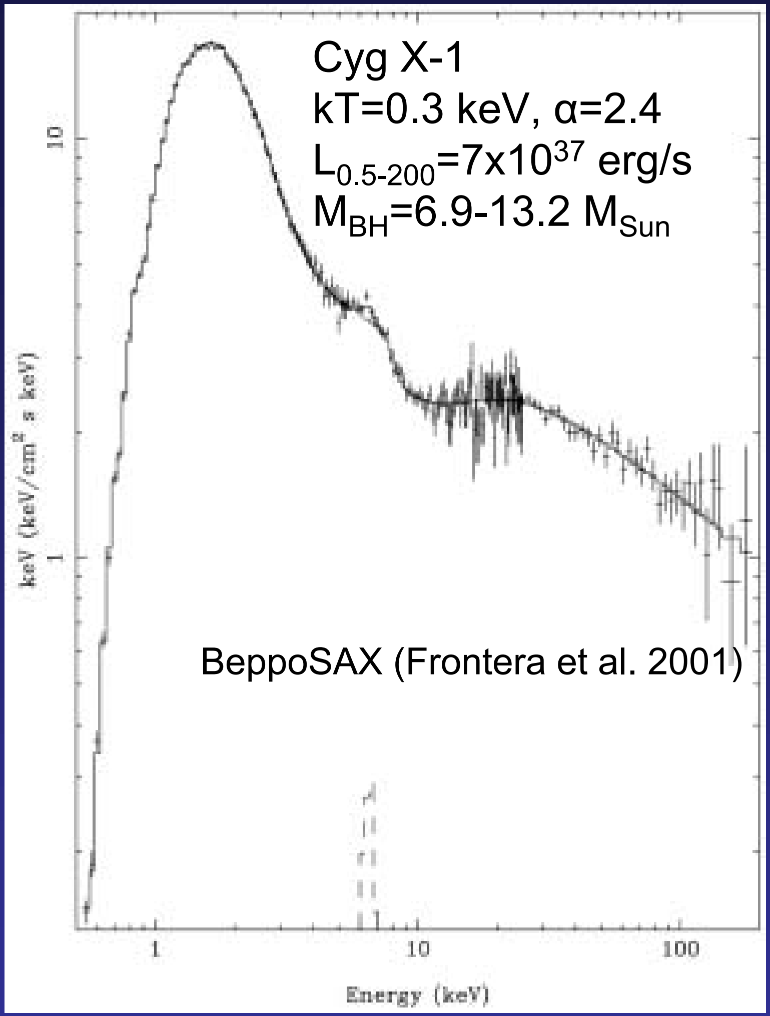
M101-114
QSS-MNOH
kT=0.13 keV
L_0.3-7=4.3x10^37 erg/s
channel energy (keV)
residuals

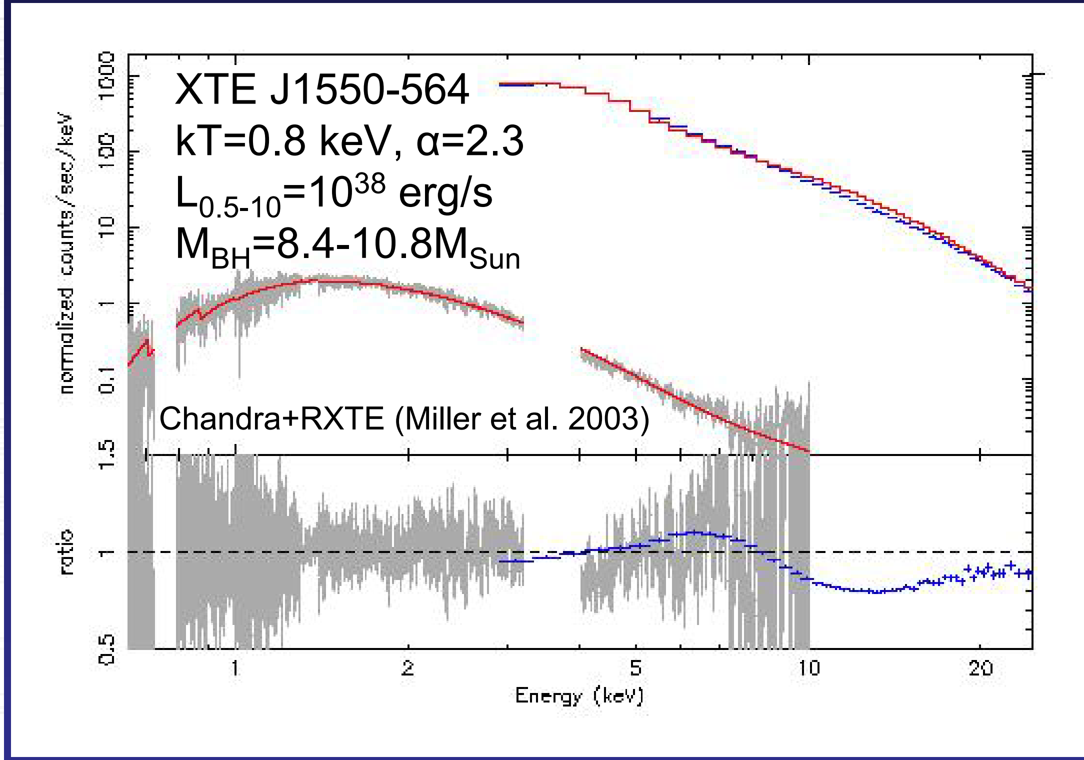
Red: SSSs Blue: QSSs



What are the Quasisoft Sources?

- They are almost certainly not WDs.
- They may be accreting neutron stars of stellar-mass BHs. *In this case they are introducing us to a portion of the parameter space that has not yet been explored*.
- The most natural explanation may be that they are accreting IMBHs.
- Note that they represent a simple extension of observed properties of Galactic BHs.





Whatever they are, the discovery of QSSs may be one of *Chandra*'s significant discoveries.

Accreting Intermediate-Mass Black Holes

- The first generation of stars was likely dominated by high-mass (~1000 M_{Sun}) stars. Their demise may have produced IMBHs.
- We don't know about the properties of any early binaries. But, if any old IMBHs are accreting today, the donors must be of low mass.
- Some ULXs are found near star-forming regions.
- We therefore consider a model in which old IMBHs capture main-sequence stars as they pass though star forming regions.

Results: Only low-mass stars will overfill their Roche-lobes before leaving the main sequence.

Analytically:

$$M_d/M_{Sun} < 1.4\ \alpha_{cric}^{-1}\ (M_{BH}/100M_{Sun})^{1/7}$$

For likely values of α_{cric} and

$50\ M_{Sun} < M_{BH} < 1000\ M_{Sun}$

$$(m_d)_{max}: 1.25\text{-}2.7\ M_{Sun}$$

For mass transfer from a main sequence star:

$$m_{dot}=2.7\text{x}10^{-11}\ M_{Sun}\ yr^{-1}\ q^{-2/3}$$

where $q=m_d/M_{BH}$

The observed luminosity is a direct measure of q.

$$q^{2/3}=(\xi/0.1)\ 1.6\text{x}10^{35}\ erg\ s^{-1}\ /\ L$$

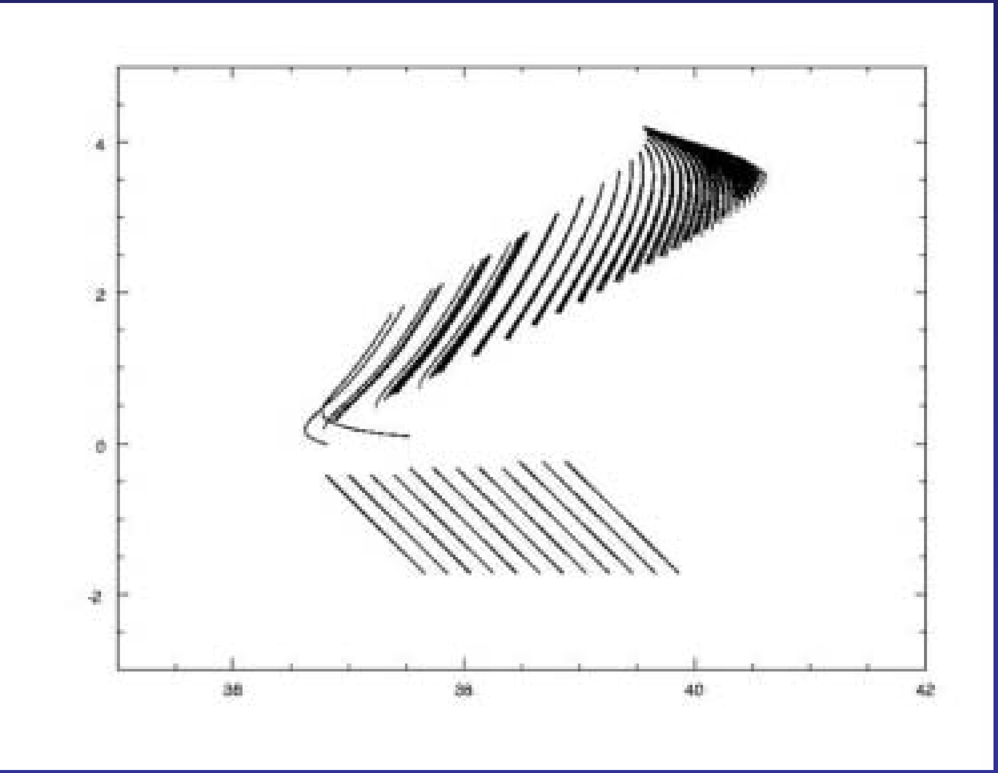
The orbital period is a direct measure of m_d.

$$P=8.9\ hr\ (m_d/M_{Sun})$$

These systems will *not* be found near regions of star formation. If dynamical friction influences their orbits, they will be near the galaxy centers during the times of peak activity.

Giant Donors

- For giant donors the situation is more complex, as the core mass of the donor star also plays a role.
- Typical mass transfer rates are higher



- These systems should be found near star forming regions.
- Their orbital periods are generally longer.

Summary

- Galaxies are rich in SSSs and in QSSs.
- We are faced with the challenge of understanding the nature(s) of the members of each of these classes of X-ray sources.
- Some SSSs and some QSSs may be IMBHs.

Whatever the nature(s) of SSSs and QSSs

- IMBHs need not be ultraluminous.
- Binary evolution can provide important and testable predictions about the properties of accreting IMBHs.
- The further assumption that IMBHs capture stars in star forming regions leads to predictions about luminosity as a function of source location within galaxies and as a function of galaxy types.